Digital audio effects and physical modeling

Alexandros Kontogeorgakopoulos, Claude Cadoz

DIGITAL AUDIO EFFECTS AND PHYSICAL MODELING

Kontogeorgakopoulos Alexandros

Cadoz Claude

ACROE-ICA laboratory
INPG, Grenoble, France

46 Av. Félix Viallet -F-38000
Grenoble

ABSTRACT

This article describes a research oriented in creating physical models that would transform and process sounds using the CORDIS-ANIMA formalism [1]. Basically the idea was to explore for the first time systematically the capabilities of this physical modeling language and more precisely the GENESIS [2] environment for the creation of Digital Audio Effects (DAFX). This presentation introduces some elementary signal processing operations and properties using the compositional blocks of CORDIS-ANIMA. Also two physical models will be described that they behave like some classical filters and time varying filters. The idea and the challenge is to give a physical meaning to these widely used algorithms.

1. INTRODUCTION

Digital audio effects – as an acronym DAFX – are digital systems that modify audio signals [4]. These transformations are made according to some sound control parameters that the algorithm permits and deliver output sounds. Control, in the broad meaning of the word, encompasses every possible method available to the user for accessing the various parameters of the system.

Many taxonomies for the digital audio effects were used. It is possible to classify most of the audio effects using an historical approach, an approach based on the complexity of the processing, on the methodology, on the cognition and in the perception [5]. Also taking an into account the context of our research, it would be possible to classify the DAFX in two main categories (mainly used to classify the sound synthesis techniques): the sound transformations and effects using i) signal processing techniques (in this case the discrete-time system is described as an abstract mathematical operator that takes the input sound sequence and transforms it into another sequence) and ii) physical modeling techniques (in this case the discrete-time system is described as a digitally simulated physical system following the principles of the Newtonian mechanics that takes the input sound sequence temporally described and transforms it into another sequence).

Physical Modeling is increasingly used and applied for musical purposes [9]. Generally it is proposed as a convincing and realistic synthesis of real acoustical instruments. Recently it has been demonstrated that the mass-interaction physical modeling scheme can be a general means for creating music than just sound synthesis [2].

In this framework of using the mass-interaction scheme from the CORDIS-ANIMA formalism and the GENESIS interface as environment for computer music creation we will present the use of this physical modeling approach to transform and process prerecorded sounds or sounds synthesized with this technique. This work will complete the possibilities of the GENESIS compositional environment based on the idea of "Physical Thinking".

This research is only the first step in this totally different approach of designing Digital Audio Effects systems. The aim of this work in the future is to lead to new DAFX algorithms, new ways of thinking of sound transformation (the algorithms will be described in a physical modeling language and not using the signal processing formalism) and a new way of controlling these systems using gestural force feedback devices [3].

2. CORDIS-ANIMA AND GENESIS

CORDIS-ANIMA is a digital, real-time, object modeling and simulation system. It provides reproductions of physical objects from the real world. The fundamental elements of CORDIS-ANIMA are a set of modules and functions that are the very elements of the modeling domain, but are at the same time the elements of the simulation. The model has the form of a network of those modules: The mass-like elements <MAT> and the physical interactions <LIA> between them. The last ones can be linear (elasticity forces, friction forces) or non-linear (a non-linear physical link which models the contact through an interaction conditioned to position and an another physical link where we have together non-linear viscosity and a non-linear elasticity defined by the curves force-distance and force-relative velocities). As a set of elements and combination rules, CORDIS-ANIMA is a language. It not only enables the description of objects from the physical world, but also their reproduction in the virtual space of simulation. This language, which allows high modularity will be used for the conception and the construction of our models that will serve as digital audio effects units.

The GENESIS environment is based on the topological CORDIS-ANIMA mass interaction system [6]. It is a user interface, dedicated to musical creation, that allows the user to design his physical models with the CORDIS-ANIMA language thanks to various model editing functions and various tools to define the parameters, observe the movement of the models, hear the sound that they produce, etc…The basic modules for GENESIS are the MAS for the inertia (one-dimensional movement, parameters: M the mass and the initial conditions X0 for the position and Vo for the velocity), the SOL for the fixed point (parameters: the initial condition X0 for the position), the REF for the visco-elastic interaction MAS-MAS or MAS-SOL (the interaction force is calculated in function of parameters: Z for the damping and K for the stiffness) which is combination of two more elementary elements RES for the elasticity and FRO for the viscosity, the CEL for the combination SOL-MAS-REF (it's actually an elementary oscillator), the BUT which is a REF conditioned to the position (parameters: all the REF parameters and the threshold S0 where for values below S0 the REF interaction is activated), the LNL where we have together a non linear viscosity and a non linear elasticity defined by the curves force-distance and force-relative velocities (parameters: the discrete points and the interpolation formula that defines the curves).

3. DIGITAL AUDIO EFFECTS BASED ON PHYSICAL MODELS

3.1. Simple Signal processing

We will present how we can realize some elementary signal processing operations using the compositional blocks of CORDIS-ANIMA. Of course our aim is not to treat the signals using mathematical operators implemented with these mechanical structures, we just want to present a wide plan of the possibilities or the toolbox we have when we are using physical modeling for the purpose of signal processing.

3.1.1. Feed forward interconnection link

We have two ways to connect two mechanical systems. It is possible to consider as the output of the first system and as the input of the second system either the force or the position, even though the variables in the Newtonian mechanics are duals and it's impossible to separate them. With the computer simulation and real time control we are forced into doing that. In general all physical communications (which are intrinsically non-oriented) are presented by two-way communication carried out by divisible input/output pairs (this is a constraint inherited by the information theory and the capabilities of the technology). So when we want to design a feed forward interconnection link (this is the case when we interconnect digital audio effects although with the force-feedback connection –something possible with CORDIS-ANIMA we may have interesting results) we have four possibilities (we will present them using the CORDIS-ANIMA formalism and the GENESIS symbolism). Something very important that we must not forget is that Genesis is always normalizing the output. So if we have a very weak signal it is still possible for it to be heard with the maximum amplitude; however if it is combined with other signals it may not be heard at all. So important is not the absolute amplitude of the output of one subsystem but the relative amplitude considering the other subsystems that are participating in the generation of the final sound.

- Position as Output/Force as Input

This is the more usual case. We are searching the following relation (figure 1): $F_1 \propto x_1$

If we use as LIA F_k (from the CORDIS_ANIMA algorithms we get the equation $F_k^{j->i}(n) = -k_{ij}[x_i(n) - x_j(n)] = -k_{ij}\Delta x_{ij}$) we can see that for $k_{ij} \approx 10^{-10} \,|\, X_{2-INITIAL} \,| << |\, \bar{X}_1 \,|$ we get this condition (system 2 is passive). The input/output relation is $-F_1 = -kx_1$. Instead of F_k we can use F_z. In this case we will have an undesired high pass filtering, as we will see in the next paragraph. Some times this is preferred because using interactions based on friction forces we ensure that approximately we won't disturb the modes of the system; we will disturb only the amplitude of those modes.

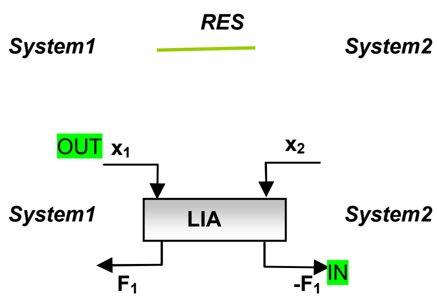

Figure 1. Interconnection of systems - Position as Output/Force as Input case using the GENESIS and the CORDIS-ANIMA symbolism

- Force as Output/Position as Output

In this case the first system has to be terminated by a stable point; only in this way can we get a force as output. We are searching the following relation (figure 2): $x \propto F_1$. If we change this point with a CEL with a flat transfer function (we can get this if $m = \frac{k}{F_s^2} = \frac{z}{F_s}$ according to next paragraphs) and a very large mass comparing to the masses of system that we use it’s output (so we assume that this mass is stable for that system) and we also ensure that the initial positions of the system 2 (passive system) are negligible comparing x produced by the algorithm of the mass so that $F_2 \ll F_1$, we get the conditions that we need. The input/output relation is $x = \frac{1}{mF_s^2} F_1$

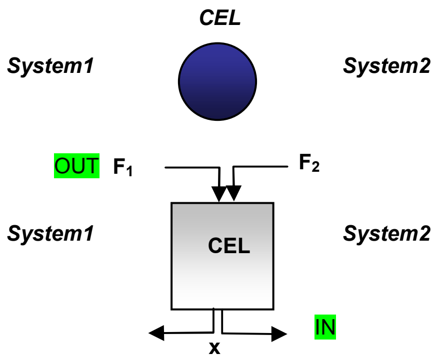

Figure 2. Interconnection of systems - Force as Output/Position as Input case using the GENESIS and the CORDIS-ANIMA symbolism

- Force as Output/Force as Input

This case is a combination of the two previous examples. We are searching the following relation (figure 3): $F_2 \propto F_1$. Using exactly the same conditions as before we get an Input/Output relation $F_2 = \frac{k}{mF_s^2} F_1$

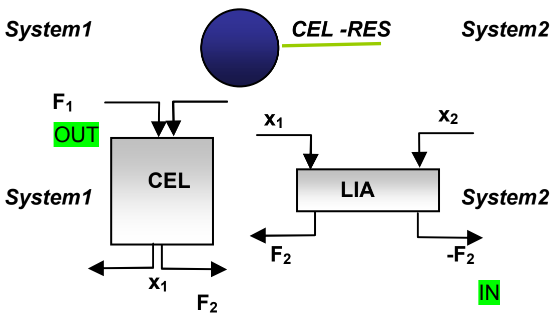

Figure 3. Interconnection of systems - Force as Output/Force as Input case using the GENESIS and the CORDIS-ANIMA symbolism

- Position as Output/Position as Input

This case is again a combination of the two previous examples. We are searching the following relation (figure 4): $x_2 \propto x_1$. Using exactly the same conditions as before we get an Input/Output relation $x_2 = \frac{k}{mF_s^2} x_1$.

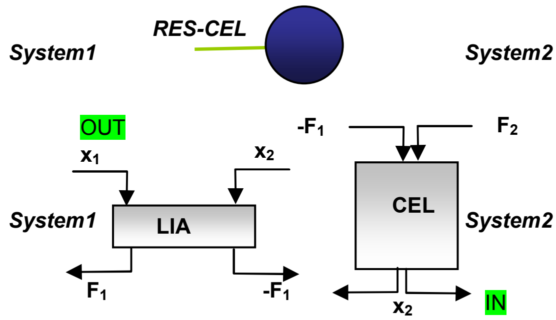

Figure 4. Interconnection of systems - Position as Output/Position as Input case using the GENESIS and the CORDIS-ANIMA symbolism

3.1.2. Addition

Using a CEL with $m = \frac{k}{F_s^2} = \frac{z}{F_s}$, we get a constant frequency response. So applying many forces to a CEL like that we get an adder. The input/output relation is: $x = \frac{1}{mF_s^2} \sum F$. We observe that there is also an amplitude modification.

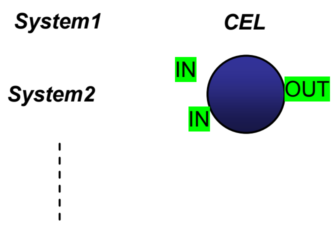

Figure 5. Addition of system output signals using the GENESIS symbolism

3.1.3. Subtraction

Using one RES with a very small negative elasticity coefficient and one RES with a very small positive elasticity coefficient and a CEL with the parameters $m = k = z$ we get the signal directly inverted. We have seen a similar network before (Position as Output/Position as Input - interconnection). This is clear from the input/output relation $x = \frac{k}{mF_s^2}(x_1 - x_2)$. As we had mentioned before, if $x_1 = x_2$ and these are not external signals, the resulted sound is not zero but a signal heard as a beat. This can easily be explained if we reach the assumptions we made about the feed forward interconnection of the system that produce the signal and the system that modify the signal; the very small feedback we get is efficient to give a result like that (after the normalization). For example if take as input two CELS with same characteristics and we subtract them we will take a beat as the output. The reason is that the final coefficients of elasticity (CEL and RES) are not exactly the same. This theoretically negligible difference gives an important audio result after the normalization (the signal before the normalization may be of order 10^{-20}).

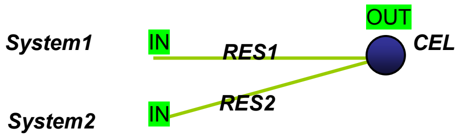

Figure 6. Subtraction of system output signals using the GENESIS symbolism

3.1.4. Amplification

The RES is working as an amplification system since the Input/Output equation is $F_k = -kx$ (the output is the force). Using it properly we are able to define accurately the amplitude in our system. It can be used with the adder as a mixing tool. Again we can use instead of RES a FRO which is safer considering the perturbation which is coming with the undesired filtering effects.

Figure 7. Amplification of system output signals using the GENESIS symbolism

3.2. Constant time filters

Now we will present some basic structures, which will behave as filters. It's well known that all linear systems are acting as filters. Especially every linear CORDIS-ANIMA network where all the <LIA> elements are terminated by a <MAT> element resulting in a frequency responsive linear combination of second order IIR filters. Every input/output pair in this network gives different liner combinations; but with the same modes-resonators. The initial conditions can also change the coefficient of the linear combination. The modes are affected only by the elasticity factors k when we have input force. The damping factors z are affecting the oscillation time.

3.2.1. Band pass filter

If we use the algorithms of CORDIS-ANIMA [7] we can find that the CEL has an input/output function (for GENESIS we give F_s=1):

$$y(n) + [-2 + \frac{k_{12}}{mF_s^2} + \frac{z_{12}}{mF_s}]y(n-1) + [1 - \frac{z_{12}}{mF_s}]y(n-2) = \frac{1}{mF_s^2}x(n-1) \qquad (1)$$

This equation describes a band pass filter realized by second order all-pole filter:

$$y(n) = b_0 x(n) - a_1 y(n-1) - a_2 y(n-2) \qquad (2)$$

This filer is the most frequently found in computer music software [8].

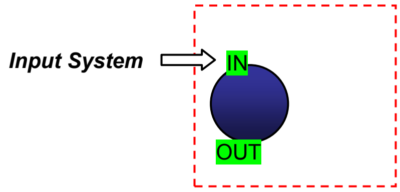

Figure 8. Band pass filter using the GENESIS symbolism

Using the formula to compute the coefficients for a desired resonant frequency and bandwidth we get the expression:

$$k = mF_s^2(a_1 + a_2 + 1) \quad z = mF_s(1 - a_2)$$
$$a_1 = -2e^{-\pi B/44100}\cos(2\pi F/44100) \quad a_2 = e^{-2\pi B/44100} \qquad (3)$$

3.2.2. High pass filter

The FRO is behaving as a high pass filter. From the CORDIS-ANIMA algorithms we have for the FRO element:

$$y(n) = -z_{12}F_s\, x(n) + z_{12}F_s\, x(n-1) \qquad (4)$$

It is a high pass FIR filter. Its amplitude response in the frequency domain is

$$H(F) = z_{12}F_s \sin(\pi \frac{F}{f_s}) \qquad (5)$$

The cutoff frequency is $f_s/4$.

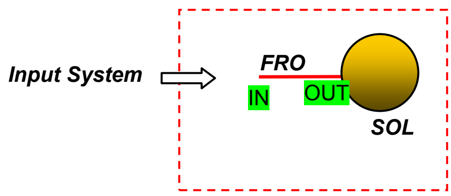

Figure 9. Low pass filter using the GENESIS symbolism

3.2.3. *Complex filters*

Using combinations of the above models we can get more complicated filters. For example we can get filter banks by using many CELs with different physical characteristics, processing the same signal in parallel and adding the outputs with the model we saw before. Systems like that can be used to easily model the behavior of complicated linear systems like the resonant boxes of musical instruments .We can also use those models in cascading form. We must not forget the feed forward connection. In this case we have to take into account the limitations of the processing machine; we are not free to calculate signals of any order (for example an extremely case 10^{-50}) and with the decoupling techniques described above it's not difficult to touch those limits.

3.3. Time varying filters

The goal is to design filters where some characteristics like the gain, the resonant frequency or the bandwidth are time-variant. The control of these parameters can be achieved using external force feedback controllers or special physical models that are controlling the dynamic behavior of the models used as variable filters. The method we will use is based on changing the physical parameters of the filters like the elasticity factor K, the damping factor Z and the mass M.

A band pass filter with time depended resonance frequency and bandwidth can be designed using a CEL module. The CEL is behaving as second order IIR resonant filter. If we change the physical parameters K, Z and M we affect the frequency response of the filter. One way to do that physically is to use not linear elasticity force. We must note that in nature we have approximately linear elasticity forces.

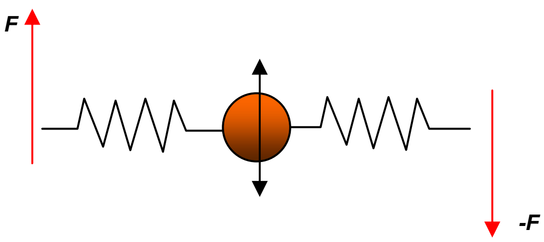

Figure 10. Stretching a real spring

Even from our everyday experience we understand that when we have the following system (figure 10 - K is depending on the elongation of the spring - usually the real world is like that) and we apply opposite forces on the side of the spring, the mass will vibrate with different frequencies. The forces are controlling the elasticity coefficient of the structure.

We can design our effect using the same principle. We will use <RES> with no linear characteristics (figure 11 – the LNK1 And LNK2 are he non-linear RES) and we will apply forces or positions on the side of the system.

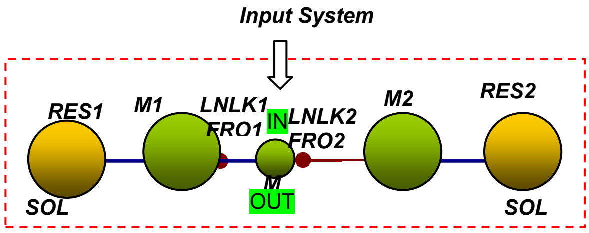

Figure 11. Time variable filter using the GENESIS symbolism

This mathematically is translated as a change in the function point of the non-linear characteristic of K (figure 12).

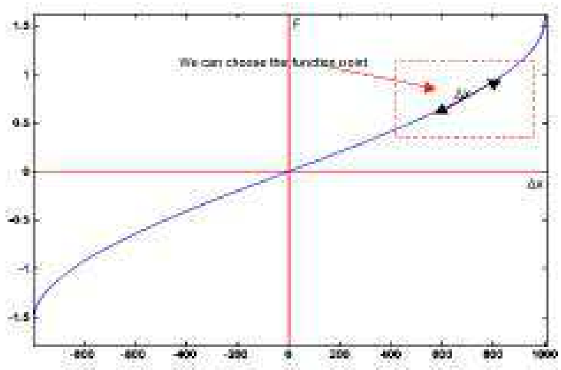

Figure 12. Non-linear characteristic of K

The gradient in every point of the characteristic is defining the elasticity coefficient. The curve has to be continuous because the transition from one region of the curve to another can't be instaneous (the non-continuities give non desirable and nearly unpredictable results).

4. CONCLUSION AND FUTURE WORKS

The most interesting point of this approach is that it allows you to create and imagine the system by "physical thinking"; it's possible to transfer your experience from the physical world and using the intuitive environment of GENESIS to build and implement the desired system. You can base your research and strategy in mechanical physics and not in mathematical operations with signals. Of course they are many constraints in this approach basically concerning the interaction of physical systems and the energetic scale at which the phenomena are taking place. The idea to explore systematically for the first time the capabilities of a general physical modeling environment as GENESIS for the creation of Digital Audio Effects (DAFX) was a challenge. This approach ended up very interesting and hopeful.

The ambition to create and imagine the processing system by "physical thinking" can be a reality with a modeling language like CORDIS-ANIMA and the helpful interface of GENESIS. We certified that it's possible to transfer your experience from the physical world to build and implement the desired system with this environment.

This research was only the first small step in this totally different approach of designing Digital Audio Effect systems. The aim of this work is to lead in new DAFX algorithms, new ways of thinking about sound transformation and probably a new way of controlling these systems using gestural force feedback devices.

Many steps have to be yet taken in understanding and transferring the knowledge and experience from the domain of Digital Audio Effects using signal-processing techniques to the physical modeling area. We believe that by building a stable and complete research framework we will open a whole new chapter in how we process sounds to create music.

5. REFERENCES

[1] Cadoz C., Luciani A. and Florens J. L. "CORDIS-ANIMA: A modelling and Simulation System for Sound and Image Synthesis – The General Formalism", *Computer Music Journal 17(4) 1993*.

[2] Castagne N., Cadoz C. "Creating music by means of 'Physical Thinking': The Musician oriented GENESIS environment", *Proceedings of the 5ith International Conference n Digital Audio Effects (DAFX-02),* Hamburg, Germany, 2002

[3] Cadoz C., Lisowski L. and Florens J. L. "A modular Feedback Keyboard design", *Computer Music Journal 14(2) 1990*.

[4] Udo Zolzer, *Digital Audio Effects,* John Wiley & Sons Ltd 2002

[5] Verfaille V., "Effets audionumériques adaptifs : théorie, mise en œuvre et usage en création musicale numérique", *PhD University of Aix-Marsaille II, France,* 2003

[6] Incerti E., "Synthèse de sons par modélisation physique de structures vibrantes : application pour la création musicale par ordinateur", *PhD Institut National Polytechnique de Grenoble, France,* 1993

[7] Cadoz C., Luciani A. and Florens J. L., "The physical Model, Modelisation and Simulation Systems for the Instrumental", In *Representation of Musical Signals*, G. De Poli, A. Picciali, C. Roads, Ed. MIT Press, 1991

[8] Dodge C., Jerse T.: *Computer Music: synthesis, composition and performance,* second edition, Schirmer Books New York, 1997

[9] Borin G, De Poli G. and Sarti A. : "Algorithms and Structures for Synthesis Using Physical Models", *Computer Music Journal 16(4), 1992*